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UNDERINVESTMENT AND INCOMPETENCE AS RESPONSES TO RADICAL INNOVATION:

EVIDENCE FROM THE PHOTOLITHOGRAPHIC ALIGNMENT EQUIPMENT INDUSTRY.

Rebecca Henderson

WP 3163-90-BPS May 1990

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Abstract

Radical innovation often drastically undermines established firms. Despite evidence suggesting that these failures are driven by organizational failure, formal research has focused upon the conditions under which established firms will fail through underinvestment, rather than through bureaucratic inertia or incompetence.

Using an unusually comprehensive data set that includes data about every research project initiated by every firm in the photolithographic alignment industry, I show that incumbents were systematically less effective than entrants in their attempts to exploit major innovation. The results are consistent with existing theories of investment behavior, but highlight an urgent need to develop rigorous theories of organizational capability.

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I Introduction

Few established firms prosper when an industry faces revolutionary or "radical" technological change. A number of studies have documented the ways in which established firms cling to old technologies in the face of change (Cooper and Schendel, 1976) or introduce new products that are markedly inferior to those introduced by entrants (Clark, 1987). Established firms appear to exploit minor or "incremental" technological change to great advantage, but to succumb to organizational inertia when confronted with more dramatic challenges (Burns and Stalker, 1966; Daft, 1982; Ettlie, Bridges and O'Keefe, 1984). Although they often invest heavily in new technologies their research is significantly less effective, and entrants with much smaller research and development budgets often succeed in dominating the industry.

There has been surprisingly little work in the economics tradition exploring this problem. With the notable exception of work by authors such as Simon, (1955) Cyert and March, (1963), Arrow, (1974), Nelson and Winter (1982), and Kreps and Spence, (1983), the theoretical literature has focused upon the circumstances under which established firms will invest more or less in innovation than entrants, rather than upon the conditions under which their research will be more or less effective.

Gilbert and Newbery (1982) showed that an incumbent monopolist has a greater incentive to invest in incremental innovation, because the market power of the established firm allows it to extract greater benefit from an incremental innovation than an entrant is able to. In contrast, Reinganum (1983) showed that, under some plausible assumptions, established firms have a smaller marginal incentive to invest in radical innovation than entrants. Intuitively, this is because established firms fear the cannibalization of their existing products. Established firms and entrants can expect the same revenues from the successful introduction of a new technology, but established firms will loose revenues from their existing markets if the new technology is introduced. Both Gilbert and Newbery and Reinganum defined radical and incremental innovation in the sense first advanced by Arrow (1962), who suggested that incremental innovations are relatively "minor" innovations that continue to compete actively with the previous generation of the technology, while radical innovations are so great an advance that the older technology is

driven from the market. Formally, he suggested that the optimal monopoly price of a radical innovation is less than the marginal production cost of the previous technology.

Models in this tradition have been developed by a number of other authors. (Baldwin and Scott, (1987), and Reinganum (1989), provide excellent overviews of this literature.) In general, they assume that incumbents and entrants have equivalent capabilities, and therefore that their research efforts will be equally effective. They thus suggest that radical technological change so often displaces established firms because established firms on average invest less than entrants in its development.

This conclusion is in contrast to the perspective developed by organizational theorists such as Burns and Stalker (1966), Galbraith (1973), and Tushman and Anderson (1986), and by economists such as Arrow (1974), Kreps and Spence (1983) and Nelson and Winter (1982). Authors in this tradition model firms as entities whose limited information processing abilities force them to develop organizational structures and specialized information processing assets that are specialized to the market and the technology in which they compete. These assets are a source of advantage as long as the firm's environment remains stable, and partially explain why established firms are so successful in their attempts to introduce and exploit minor or incremental innovation, but they handicap established firms once they are forced to respond to radically different markets or technologies.

These authors define radical innovation as innovation that presents quite different organizational and information processing challenges because its exploitation requires the understanding and integration of wholly different kinds of information (Tushman and Anderson, 1986). Entrants to the industry either build new organizations optimized to develop this kind of information or enter from related industries where they have already gained experience with the new technology. Organizational theorists suggest that incumbent firms are unable to duplicate entrant behavior through "bureaucratic inertia," or the inability to recognize the nature of the threat with which the organization is faced and to reorient themselves in time (Daft, 1982), while Arrow, and other researchers with similar perspectives, suggest that incumbents choose not to duplicate entrant behavior because of the sunk costs represented by their existing information

processing assets. Although the existing organization may not be not optimally efficient in exploiting radical innovation, it is cheaper to tolerate this inefficiency than to incur the fixed costs necessary to develop a new organization from scratch (Arrow, 1974).

Although these insights are broadly consistent with a great deal of anecdotal evidence and with research in the behavioral tradition (Moch and Morse, 1977; Dewar and Dutton, 1986) with a few notable exceptions there have been surprisingly few attempts to incorporate them into formal models of firm behavior or into empirical research (For exceptions, see work by Jovanovic, (1982), Lippman and Rummelt (1982), Ericson and Pakes (1989), Pakes and Ericson (1989)). A great deal of detailed empirical work has explored the impact of investment in research and development on firm productivity (See, for example, work reported in Griliches (1987)), but in general this research has neither distinguished between radical and incremental innovation nor investigated firm specific effects in any detail. A few researchers have examined the extent to which large firms invest more in research or are more likely to be the source of major innovations (See for example, work reported in Freeman, (1982), and Cohen and Levin, (1989), also work by Pavitt, (1987), and Acs and Audretsch, (1988)), but this research has either not distinguished between minor and major innovations or has used aggregated data and a limited set of variables to explore the impact of firm specific effects on productivity.

This failure to integrate theories of firm capability into empirical studies of the impact of technological innovation may result from the fact that these types of explanations yield qualitatively similar predications to the class of explanations that focuses on investment behavior. Both suggest that established firms will be more likely than entrants to introduce incremental innovations, since established firms will not only invest more in incremental innovation in an attempt to extend monopoly power but will also have more effective research and development efforts since they have the benefit of historical experience with the technology. Similarly the two classes of explanation suggest that established firms will be less successful in the face of radical innovation both because in some circumstances they will invest less for fear of cannibalizing their existing revenues, and because their research and development efforts will be less effective than those of entrants.

However recent work by Henderson and Clark (1990) suggests that it is increasingly important to explicitly distinguish between the two effects and to understand the interactions between them. They suggest that a significant number of innovations are "architectural." Architectural innovations are incremental in the economic sense in that they do not provide dramatically different or improved benefits to their customers, and they continue to actively compete with existing products, but they are radical in the organizational sense in that established firms find them extremely difficult to develop. Architectural innovations are likely to be the focus of complex competitive dynamics since the strategic incentives to invest in them that flow from market position run counter to the incentives that flow from the relative research efficiency of actual and potential players in the industry, and they cannot be easily understood through the lens of the currently available theoretical and empirical results.

This paper addresses this gap in the literature through the exploration of the failure of established firms to survive architectural innovation in the semiconductor photolithographic alignment equipment industry. The author obtained research and development costs, sales, and organizational and technical information for every product development project initiated by every firm in the semiconductor photolithographic equipment industry for the period between the foundation of the industry in the early 1960s and 1986. Four waves of architectural innovation shook the industry during this time, each of which saw the replacement of the industry leader with a new firm. Thus the data set affords a unique opportunity to explore the dramatic competitive effects of technological change.

I differentiate between the decision to invest in a particular research program and the effectiveness with which the research was carried out, and show that established firms failed to successfully exploit architectural innovation in the industry because although they consistently invested an equivalent amount in innovation, their research was consistently less effective. Not only were established firms less successful in their attempts to introduce technically successful new products, but they were also less able to successfully commercialize the products that they did develop. I show that this failure is consistent with the hypothesis that established firms develop

specialized organizational capability during the course of their historical experience with incremental innovation that handicaps their attempts to respond to more radical change.

The paper is unique in explicitly incorporating both explanations based upon investment behavior and explanations based on the concept of firm heterogeneity into its analysis of the problem of established firm failure in the face of radical innovation, and in the detail and comprehensiveness of the data set upon which it is based. My results are exciting and suggest that we cannot assume that innovation that is radical or incremental in the economic sense is also radical or incremental in the organizational sense, and that the competitive implications of technological innovation cannot be understood without an appreciation of the qualitatively different capabilities of entrants and incumbents in the face of different types of innovation. They have broad implications for theories of industry and firm evolution.

The next section describes the data upon which the study was based, and Section 3 describes the empirical model and the results. The paper closes with a discussion of the implications of this research for further work.

II The Data

The data for this study were collected during an eighteen month, field based study of the photolithographic alignment equipment industry conducted from the spring of 1987 to the summer of 1988.

Photolithographic aligners are pieces of capital equipment used in the manufacture of semiconductors.[1] Improvements in photolithographic alignment capability have been critical to the dramatic improvements in performance and reductions in cost that have characterized semiconductors over the last twenty years, and the industry has shared in the rapid growth of the semiconductor industry.

Alignment equipment is technically very sophisticated, and technical change in the industry has been very rapid. The first aligners were introduced in the early sixties. They were built by teams of two or three designers and cost less than five thousand dollars. A modern aligner can cost

as much as two million dollars, and its design can occupy the energies of more than a hundred engineers for several years. A steady stream of incremental innovation has been responsible for much of the improvement in alignment performance, but the industry has been shaken by four major innovations over the last twenty five years. (Henderson, 1988, gives technical descriptions of each type of equipment.)

Henderson and Clark (1990) suggest that these innovations were "architectural" innovations. They drew upon little dramatically new science, and initially actively competed with the existing technology, providing only marginal improvements in capability at somewhat higher prices. However they raised significant organizational challenges for the established firms, making a substantial fraction of their organizational capabilities obsolete in subtle and complex ways.

Table (1) shows the sales history of the industry by generation of equipment. The older generations continued to sell well despite the introduction of equipment incorporating the next radical innovation because the semiconductor industry itself is highly fragmented, and a significant proportion of the semiconductors manufactured have not required the very expensive, leading edge capability of the latest generation of alignment technology. Table (2) gives share of sales in each generation for the firm that dominated the previous generation and for the most successful new entrant. Although nearly every incumbent invested heavily in the next generation of technology, every generation was dominated by an entrant to the industry. The empirical work presented here explores the relative contribution of investment behavior and organizational effectiveness to explaining this history.

The core of the data is a panel data set consisting of research and development costs and sales revenue, by product, for every product development project conducted in the industry's history. These data are supplemented by a detailed managerial and technical history of each project.

The data were drawn from a wide variety of sources. The trade and technical press were used to identify major innovations and the names of firms that have been active in the industry. For each product development project identified during the course of the research, including those conducted by Japanese companies, at least two people who were actively involved with the project

were interviewed.[2] Interview data was combined with internal firm records and with data obtained from market research and consulting firms who actively follow the industry. A written history of each project and of each firm's involvement in the industry was then circulated to those who had been interviewed and to other knowledgeable individuals in order to confirm the data's validity. In the few cases where it proved impossible to interview anyone involved with the project, the project's history was constructed through secondary sources and through interviews with industry experts.

Forty nine product development projects were identified during the course of the research. Throughout the data gathering effort a systematic effort was made to avoid the sample selection bias that would result if firms that tried to enter the industry and failed were omitted from the data set, and a variety of strategies were used to ensure that every development project undertaken in the industry's history, including those undertaken by failed entrants, was included. The trade journal Solid State Technology, which follows the industry and has been published monthly since 1960, lists all new products announced in the field. Data was collected about every product or prototype announced through this listing (which is free). In addition, throughout the eighteen months of the data collection effort, all respondents were asked to direct the researcher to other firms and individuals who had also been active in the industry. The industry's technical community is very small - even today about fifty engineers dominate the technology - and I believe the data set to be a comprehensive one.

No quantitative information was collected about basic scientific research relevant to the industry conducted either within university or government labs or within firms active in the industry. Discussions with industry experts suggested that although such research was occasionally important, it was very quickly diffused within the industry's technical community, and was not an important source of competitive advantage.

It proved to be difficult to obtain accurate or meaningful price or cost data. The price of an aligner is negotiated between the supplier and the customer. Since each sale includes a different bundle of product options, transaction prices have varied widely, and few records of either the price or manufacturing costs of individual shipments have survived. However since aligner

capability is so fundamental to the technical success of a semiconductor manufacturer, competition has historically focused around technical excellence, and price has been of only secondary importance. In general, customers have used a lexographic ordering of preferences to choose products, using technical capability as their primary criterion and sales and service expertize and reputation as secondary and tertiary criteria (Henderson, 1988).

III The Results.

The unique scope and comprehensiveness of the data set allows for the estimation of three distinct effects: the determinants of investment in research and development, and the determinants of technical and commercial success at the project level. This separation allows for an explicit comparison between the contribution of the level of investment in research and the contribution of relative research productivity as explanations for the failure of established firms in the industry, and for a separate exploration of the factors that drive technical and commercial success.

Investment in research, technical success and commercial success are modeled as a recursive system. Although in many industries this would be an unwarranted approximation, it accurately describes research in the photolithographic industry, since firms must make the full investment in the engineering effort necessary to build a new aligner before they know whether the aligner will prove to be either technically or commercially successful. Semiconductor production technology, and its associated demands on aligner technology, changes very fast, so that the success of any particular aligner can only be determined once it has been quite extensively used in production environments.

Research and Investment

A number of factors determine a firm's investment in research in any particular project: expected demand and profit; the firm's market power; its existing organizational capability; its competition; and the nature of the innovation that it faces.

All other things equal, I expect firms to invest more in projects for which they expect greater demand and greater profits. The theoretical literature suggests that there is no simple

relationship between competition and research intensity (Baldwin and Scott, 1987; Reinganum, 1989) but from my qualitative knowledge of the industry I expect investment to fall as competitive intensity increases.

For both strategic and organizational reasons I expect incumbents to invest more in incremental innovation than entrants. Gilbert and Newbery (1982) suggested that incumbent firms invest in incremental innovation in order to exploit their existing position in the industry, and I thus expected incumbents' investment in incremental innovation to be positively correlated with their market power. Similarly, building on my hypothesis that firms with greater experience in an industry will be more effective in their attempts to introduce incremental innovation, I expect firms with greater experience to invest more in incremental innovation since for any given level of investment they expect a greater marginal return.

I cannot predict whether incumbents are likely to invest more or less than entrants in architectural innovation, since predictions derived from organizational and economic theory run directly counter to each other. This is shown graphically in Figure (1).

On the one hand, Henderson and Clark (1990) show that architectural innovation in the industry present established firms with very significant organizational challenges, since it makes a critical portion of their existing organizational knowledge partially obsolete. Arrow (1974) suggests that in these circumstances established firms will continue to use their existing capabilities despite their lower effectiveness because of the high fixed costs necessary to create new capabilities, and thus that their research efforts are likely to be significantly less effective.

Since, in conformity with Arrow's suggestion, incumbent firms in the industry continued to use their existing organizational assets to exploit architectural innovation,[3] I expect incumbents considering only the impact of expected research productivity on their investment decision to invest significantly less than entrants in architectural innovation in the expectation that the marginal research productivity of their research efforts will be significantly lower.

On the other hand, the available evidence suggests that these architectural innovations, despite their very significant organizational implications, were incremental in the economic sense - that is that established firms could hope to extract greater profit from their introduction than

entrants. Architectural innovations competed actively with the previous generation of equipment when they were initially introduced, and customers in the industry expressed very strong preferences for equipment built by their existing vendor, all other things equal, because there significant switching costs are incurred in buying equipment from a new vendor.[4] Thus from Gilbert and Newbery (1982), established firms should have expected greater marginal benefits than entrants from the introduction of any particular architectural innovation.

Since these two effects run directly counter to each other, without further knowledge about their relative magnitudes in any particular setting, I cannot predict whether incumbents invested significantly more or less than entrants in architectural innovation.

A full description of all variables together with basic descriptive statistics is given in Table (3). A log linear specification was used as one of the most general specifications available. A number of alternative specifications were also explored without changing the direction or significance of the results. The results of the analysis are given in Table (4). The results convincing reject both the null hypothesis that the investment patterns of incumbents and entrants cannot be distinguished, and the null hypothesis that investment is unrelated to the incremental or architectural nature of an innovation.

Investment in research, defined as person years invested in new product development in the first three years of the project's life, is driven by demand in all specifications, as predicted, where demand is measured as sales of semiconductor devices in the three years following product introduction. Investment increases with the hazard rate, or, as might be intuitively expected, as fewer competitive research projects are initiated. Alternative measures of competition, including the number of entrants to the industry and the magnitude of their investments, left this result unchanged.

The dummy variables (Contact+Proximity) and (S&R1+S&R2) were included in the specification to capture the effect of increasing product price and technical sophistication on research investment. Contact and proximity aligners rely on the simplest science. First and second generation steppers on the most complex, and scanning projection aligners, the reference group, are intermediate in complexity between the two (Henderson, 1988). Prices for all generations of

aligners have increased over time, but in general contact and proximity aligners are cheaper than scanners, which are cheaper than first and second generation steppers. As expected, firms invested more heavily in more complex and more expensive technologies than they did in those that were less complex and less expensive. Specifications using the available, very dirty, price data produced similar but less significant results.

Specification (1) tests for differences in incumbent and entrant investment behavior. As expected, incumbents invested significantly more in incremental innovation than entrants. The estimated coefficients suggest that, all other things equal, incumbents invest nearly 70% more effort in incremental development than do entrants. This is consistent with the hypothesis that established firms invested more in incremental innovation than entrants both because they expected to be able to extract more benefit from it and because they expected to be able to exploit it more effectively.

The results of specification (2) confirm Gilbert and Newbery's hypothesis that an incumbent's investment in incremental innovation will be positively correlated with market power, since it shows that incumbent investment in research was correlated with market power, where market share was measured by the firm's market share in the previous generation of the technology in the year in which the firm's investment was made. The results

Specification (3) tests for differences between incumbents' and entrants' investment in incremental and architectural innovation. Although I cannot reject the hypothesis that entrants do not distinguish between incremental and architectural innovations in making their investments, the results convincingly suggest that incumbents invest significantly less in architectural innovation than they do in incremental.

This result is consistent with two possible explanations. On the one hand, it is consistent with the idea that the major innovations in the photolithographic industry have been radical in Reinganum's and Arrow's sense - and that incumbents have invested marginally less in them for fear of cannibalizing their existing revenues. On the other, it is consistent with the idea that although architectural innovation in the industry has been incremental in the economic sense, since incumbents retained their existing organizational capabilities to exploit architectural innovation,

they expected the marginal productivity of their research efforts to be significantly lower than that of their efforts directed towards incremental innovation, and thus invested significantly less in its development.

The available evidence strongly supports the second explanation. In the first place, the results of specification (1) suggest that incumbent and entrant investment in architectural innovation in the industry cannot be distinguished, a result that is inconsistent with the hypothesis that architectural innovation in the industry was radical in the economic sense, and thus offered greater marginal benefits to new entrants. In the second place, the fact that entrants apparently did not expect the marginal productivity of their research to be a function of whether an innovation was incremental or architectural suggests that it was the incumbents' use of partially organizational capital that drove their investment behavior, rather than any inherent difficulty of architectural innovation per se.

Equations (4) presents a specification designed to separate the effect of the strategic incentives for investment from those stemming from differences in expected research effectiveness. Cumulative research experience with the previous technology was used as a measure of organizational capability. I expected incumbent investment in architectural innovation to be positively correlated with market power, but, to the degree that incumbents with greater experience in the previous generation were likely to labor under even greater handicaps in their attempt to exploit architectural innovation, to be negatively correlated with prior experience. Unfortunately my results suggest that the two effects cannot be explicitly distinguished. This result may flow from fundamental collinearity in the data, since both organizational experience and market power are simultaneously determined by a firm's historical success.

Technical Success

The richness of this data set allows me to test separately for the determinants of technical and commercial success. A project was defined as "technically successful" according to an informant's response to a question of the type "all in all, do you think that this project was a technical success?" Both engineers who had worked on a project and other industry experts who

were familiar with it were asked this question, and there was very close agreement in their answers. The use of a more fine grained measure of technical success, in which each project was given a score between 1 and 5, was also explored, but left the results reported here unchanged and no more significant.

I expected the likelihood of technical success to be positively correlated with both a firm's investment in research and with the investments made by its competitors, since I expected the closeness of the industry's technical community to lead to significant spillovers of knowledge between firms actively engaged in developing similar products. However I expected the relationship between research investment and the probability of technical success to be a function of a firm's prior experience in the industry in combination with whether an innovation was architectural or incremental.

From my hypothesis that the organizational capabilities developed by incumbents during their experience with incremental innovation handicap their attempts to introduce architectural innovation, I expected incumbents to be significantly less effective in their attempts to introduce architectural innovation than entrants, and to be significantly less effective in their attempts to introduce architectural innovation than in their efforts to introduce incremental innovation. Similarly, I expected incumbents to be significantly more effective than entrants in their attempts to introduce incremental innovation.

Table (5) summarizes the data. While about one half of all the projects begun by entrants were successful, incumbents were much more successful in their attempts to develop incremental innovation than in their attempts to develop architectural innovation. The results of the statistical analysis are shown in Table (6). A log linear probit specification was used to explore the data as the most general specification consistent with the use of a dichotomous dependent variable.

As expected, increasing investment in research increased the odds that a project would be technically successful. Surprisingly, increasing competitive investment in research had no significant effect, suggesting that there were minimal spillovers between rival product teams. Dummy variables were included to control for differences in any inherent technical difficulty across the generations of the technology, but were insignificant.

Specification (1) tests the null hypothesis that incumbents and entrants were equally effective in their attempts to develop incremental and architectural innovation. This hypothesis is clearly rejected. Instead, the results are entirely consistent with the hypothesis that incumbents were much less effective than entrants in their attempts to introduce architectural innovation. Specification (2) tests the null hypothesis that incumbents were equally effective in their attempts to develop architectural and radical innovation. This hypothesis is also convincing rejected.

These are very exciting results. They provide convincing empirical support for the idea that incumbents and entrants have quite heterogeneous research capabilities, and that incumbents fail in the face of architectural innovation - that is innovation that makes a significant fraction of the existing knowledge and organizational capabilities obsolete - because they attempt to exploit it using organizational capability that is much better suited to the development of incremental innovation.

More surprisingly, the data do not reject the hypotheses that entrants are as effective as incumbents in their attempts to introduce incremental innovation and that they are equally effective in their attempts to develop incremental and architectural innovation. This is in direct contradiction to my hypothesis that incumbents are likely to be more effective than entrants in the development of incremental innovation since they develop specialized organizational capability during their historical experience with a technology that is particularly well suited to the development of incremental innovation. One possible explanation for this result is that entrants only attempt to enter the industry using incremental innovation when they can exploit specialized capability developed during experience with other technologies, and can hope to compete with the incumbent firms on their own terms. A lack of data about entrants' experience in other industries prevented me from exploring this hypothesis.

Specification (3) explores the idea that incumbent firm capability is a linear function of historical experience with the technology. However comparison of the log likelihood function between the two specifications suggest that the simple distinction between incumbents and entrants is a better description of the data, suggesting that incumbent research capability is a more complex function of past experience, perhaps in combination with other unmeasured factors.

Commercial Success.

Although my analysis of change in the industry has focused primarily upon the problems incumbent firms experienced in responding to major technical change (Henderson and Clark, 1990, Henderson, 1988), there is scattered evidence that established firms also find it difficult to commercialize major innovations. Firm assets such as distribution networks, service expertize and knowledge of critically important customer demands may all become partially obsolete, triggering the types of ineffectiveness that handicap incumbent's research efforts (Freeman, 1982).

Since in this data set projects were judged to be technically successful ex post, after their performance in the market was already known, there is a danger that any positive relationship between technical and commercial success is the measurement error, rather than a reflection of the underlying dynamics of the industry. In order to control for this effect, I first explored the determinants of commercial success as a simple function of initial research investment and competitive activity.

The results of this analysis are given in Table (7). Since six development projects resulted in products that were never introduced to market, tobit analysis was used. In the absence of data about profitability, commercial success was measured as mean share of market in the first three years after a product's introduction. Share of market is probably a good proxy for profitability, since managers with experience in the industry consistently reported net profit margins on the order of 25-30% and a continuing stress on non price competition between products. Competition was measured as competitive investment in basic research in person years. Other measures of competition were explored but gave equivalent results. In order to control for the benefits of beating competitors to market, a measure of the years since first product introduction in the generation was included in the analysis.

Increased competition reduces expected share of market, but commercial success is not significantly rated to the time at which the product was introduced. The more critical results strikingly confirm my initial hypothesis. The null hypotheses that incumbents and entrants are likely to gain equivalent market shares for either architectural or incremental innovations, all other

things equal , and that incumbents are likely to be equally successful in the introduction of both architectural and incremental innovation, are easily rejected by the data. As predicted by my hypothesis, incumbents are more successful in their attempts to introduce incremental innovation than in their attempts to introduce architectural innovation, and they are also much less successful than entrants in their attempts to introduce architectural innovation. These results are consistent with the conclusions of my analysis of the determinants of technical success.

The results presented in Table (8) are even more exciting, and confirm the importance of building a richer understanding of the determinants of heterogeneous firm capability. The specifications presented in Table (8) include technical success as a determinant of commercial success. As expected, commercial success is strongly and positively correlated with technical success. The most dramatic result, however, is the finding that even after accounting for the effects of technical success, incumbents introducing architectural innovation to the market were likely to gain a significantly smaller share of the market than were entrants. The estimated coefficients suggest that entrants will gain nearly four times the market share of incumbents, all other things equal. These results are consistent with the idea that the organizational capabilities developed by incumbent firms during their experience with the previous generation of equipment handicap not only their technical development efforts, but the effectiveness of their commercialization efforts as well.

Conclusions

This paper has explored the role of both strategic incentives to invest in research and heterogeneous organizational capabilities in the history of the semiconductor photolithographic alignment equipment industry. Although my results are consistent with existing theories of strategic investment behavior, they suggest that these theories are inadequate to explain the industry's history. Instead, they strongly support the idea that established firms in the industry failed to survive the advent of radical innovation because their research efforts were significantly less effectively than those of entrants. Not only were established firms less likely to develop

technically successful products, but, all other things equal, they were also less successful in their attempts to commercialize major innovations.

This paper shows that it is as important to understand the roots of heterogeneous firm capability as it is to understand the economic incentives that constrain firms' investment behavior. By differentiating between the decision to invest in research and the effectiveness with which it was carried out, I was able to show that in the photolithographic alignment industry major innovation was "architectural." Although it created significant technical challenges for the established firms in the industry, making much of their existing knowledge and organizational capability obsolete, it was relatively minor or incremental in the economic sense, so that established firms had at least the equivalent incentives to invest in it. Thus the persistent pattern of established firm failure that characterized the industry's history was driven by the obsolescence of organizational knowledge, and not by a pattern of underinvestment.

These are exciting results. This is one of the first systematic empirical studies at this level of detail to integrate economic and organizational theory, and the results underline the importance of accounting explicitly for the heterogeneity of both firms and innovations in empirical and theoretical studies of technical change. They suggest that the competitive implications of this kind of innovation cannot be understood without the explicit integration of classical economic frameworks with a richer understanding of internal firm dynamics, and open up a number of important research questions.

The first is that of the characterization of innovation. In an earlier paper with Kim Clark, I suggested that the simple characterization of innovations as either "incremental" or "radical" was incomplete in that it obscured the importance of innovations that were intermediate in character between the two (Henderson and Clark, 1990). We suggested that architectural innovations share many of the characteristics of incremental innovation, in that they have only minor immediate economic impact, and do not draw upon wholly different scientific principles. However established firms may find them quite difficult to exploit because they call upon a significantly different set of organizational knowledge, and established firms may find it very difficult to understand and respond to this challenge.

In this paper I have extended this argument to suggest that the historical assumption that innovations that are incremental or radical in the economic sense are also incremental or radical in the technical or organizational sense may be seriously misleading for innovations of this intermediate character. In the photolithographic alignment equipment industry, architectural innovations was "incremental" in the classical economic sense but "radical" in the organizational, so that established firms had significant incentives to invest in it but yet found it very difficult to exploit. It will be important to develop empirical methods for characterizing innovation that will enable us to identify these innovations with these characteristics.

The other research questions that this paper highlights are more far reaching. This paper suggests that it is important to build on the path breaking work of Arrow (1974), Simon (1955) and Nelson and Winter (1982) to develop theories of the firm that are as firmly rooted as the existing theories of competition. Work by scholars such as Aoki (1986, 1990) are steps in this direction.

A major challenge for this research will be the integration of traditional assumptions about firm behavior with the growing body of observation that suggests that firm capability may be uncomfortably mutable. A major focus of current research in organizational behavior and managerial studies is the search for organizational forms that will retain the ability to adopt radical innovations despite extensive experience with incremental innovation in a single technology (Hedberg, 1981; Kochan and Useem, 1990). Some authors have suggested that large Japanese corporations have quite distinct organizational forms that enable them to be significantly more innovative (Aoki, 1990; Clark, 1990). A major challenge for theoretical economic research remains the exploration of organizational capability as a competitive variable that may be as much a matter of strategic choice as investment in fixed assets, while further empirical studies of the competitive implications of heterogeneous organizational capabilities are urgently needed. Given the turbulent environment characteristic of many industries today, such exploration will have immediate practical implications.

Footnotes

1 The production of integrated circuits requires the transfer of a sequence of very small intricate patterns to the surface of a silicon wafer in a series of layers. The process of transfer is known as "lithography." In optical lithography the surface of the wafer is coated with a light sensitive chemical known as a "resist." The pattern that is to be transferred to the wafer surface is drawn onto a "mask" and the mask is used to block light as it falls onto the resist, so that only those portions of the resist defined by the mask are exposed. The resist is developed and the exposed areas are stripped away leaving the mask pattern on the wafer.

This pattern is then used as the basis for further processing of the wafer through deposition or etching. This process may be repeated as many as twenty five times during the manufacture of a semiconductor device. Photolithographic alignment equipment is used to position the mask relative to the wafer, to hold the two in place during exposure, and to expose the resist. A more detailed description of the technology is given in Henderson (1988).

2 A "product development project" was defined as any research project that the firm itself described as being designed to introduce a new model. Minor changes to existing products such as the introduction of larger lenses or more powerful sources were not defined to be new development efforts.

3 None of the established firms in the industry fired or transferred any significant fraction of their product design groups. One important design team (the group at Kasper under Karl Johansmier) left to form their own firm. This firm is characterized as an incumbent for the purposes of the analysis presented here.

4 The use of a photolithographic aligner in a semiconductor manufacturing plant requires the development of a large number of specialized assets that are specific to a particular vendor. These include peripheral equipment such as masks and wafer transport equipment, and tacit production "know-how" about the operation of a particular vendor's aligner.

Figure (1)

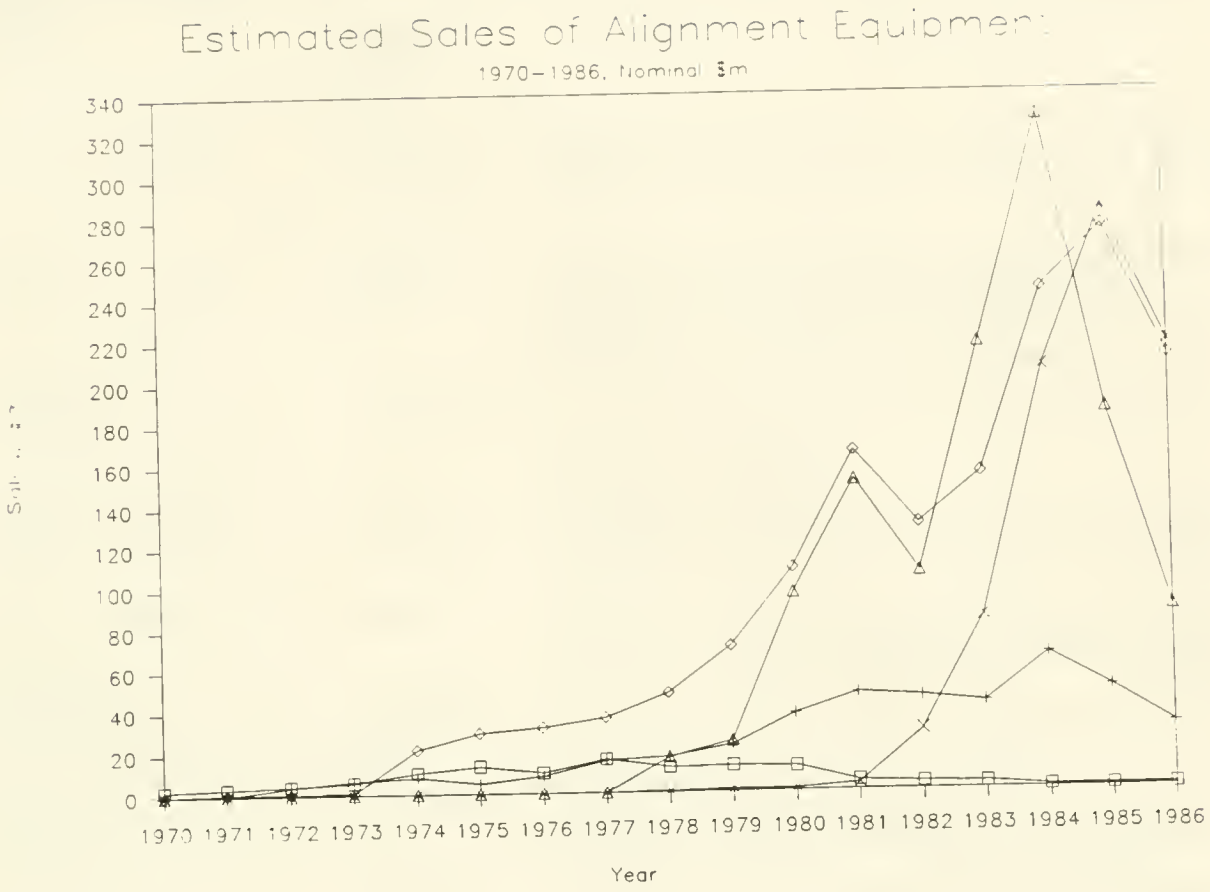
Effect on Investment Incentives of Innovation Type.

	From an Economic Perspective:	
	Incremental	**Radical**
From an Organizational Perspective:	"Minor" innovation - old product continues to be an active competitor: formally: $P_m^n > C^o$.	"Major" innovation - old product is driven from the market: formally: $P_m^n < C^o$.
Incremental Builds on Incumbent Capabilities	Incumbents expect greater marginal profits through extension of market position. Incumbents have more effective research since they have developed specialist capabilities **=> Incumbents invest more than entrants.**	Incumbents expect smaller marginal profits through fear of cannibalization. Incumbents have more effective research since they have developed specialist capabilities **=> ??**
Radical Obsoletes Incumbent Capabiities	Incumbents expect greater marginal profits through extension of market position. Incumbents have less effective research since they have developed specialist capabilities. **=> ??** *Architectural Innovation*	Incumbents expect smaller marginal profit through fear of cannibalization. Incumbents have less effective research they have developed specialist capabilities. **=> Entrants invest more than incumbents.**

Where: P_m^n is the monopoly price for the new technology.

C^o is the marginal cost of the old technology.

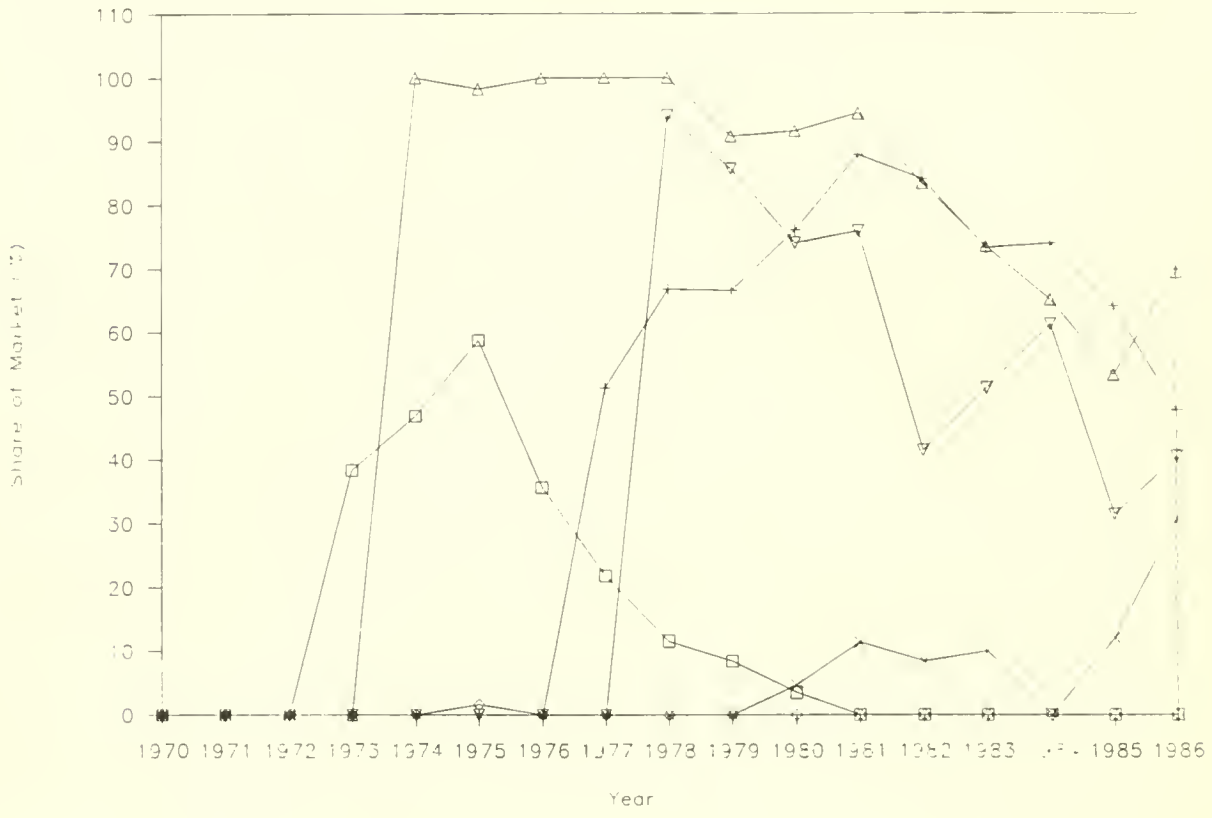
Table (1)



- Contact Printers
- Proximity Printers
- Scanning Projection Aligners
- Step and Repeat Aligners (1)
- Step and Repeat Aligners (2)

Table (2)

Estimated share of sales by the most successful entrant and by the most successful established firm of the previous generation.



	Dominant Incumbent In the Previous Generation	Most Successful Entrant
Proximity Printers	□	+
Scanning Projection Aligners	◇	△
Step and Repeat Aligners (1)	×	▽

Table (3a). Definitions of Variables.

Variable	Variable Name	Construction
Research Investment	BASRAD	Person years invested in development during the first three years of development.
Demand	DMDSAL	Average sales of semiconductor devices, in 1986$, over the first three years after the products introduction, or after the development project was terminated, if no product was introduced.
Hazard rate	HAZARD	1 / Number of other development projects in this generation of equipment.
Contact+Proximity	CONTPRX	A dummy variable set equal to 1 if the project was designed to introduce a contact or proximity aligner.
S&R. 1 + S&R. 2	SR1SR2	A dummy variable set equal to 1 if the project was designed to introduce a contact or proximity aligner.
Architectural	ARCHIT	A dummy variable set equal to 1 if the innovation is architectural.
Incumbent	INCUMB	A dummy variable set equal to 1 if the firm has previously introduced a product into the industry.
Incremental	INCREM	A dummy variable set equal to 1 if the innovation is incremental.
Entrant	ENTRAN	A dummy variable set equal to 1 if the firm has previously introduced a product into the industry.
Prev. Market Share	SHRPRV	Total market share of all the firm's products in the market the year before initiation of development.
Prev. research experience	ADJPRD	Cumulative person years invested by the firm in the previous generation, if the innovation is architectural, and in this generation, if the innovation is incremental.
Technical Success	SUCESS	A dummy variable set equal to 1 if the project met the designers' original goals.
Competitive Investment	CMBSRD	Person years invested in development development by competitors during the first three years of development of all competing products.
Market Share	OWNSHR	Mean share of market of appropriate generation, for all the years the product was available or the first three, whichever is the smaller.
Time after first introduction	INTRO	Years since the first product in this generation was introduced + 1.

Table (3b)

Descriptive Statistics

Variable Name	Mean	Std. Dev.	Minimum	Maximum
BASRAD	55.1	59.3	3.00	250
Ln(BASRAD)	3.46	1.11	1.10	5.52
DMDSAL	17.8	10.7	2.70	56.9
Ln(DMDSAL)	2.68	0.69	0.99	4.04
HAZARD	0.13	0.07	0.07	0.33
CONTPROX	0.29	0.46	0	1
SR1SR2	0.51	0.51	0	1
ARCHIT	0.45	0.50	0	1
INCUMB	0.61	0.49	0	1
INCREM	0.55	0.50	0	1
ENTRAN	0.39	0.49	0	1
SHRPRV	44.7	35.1	1	100
Ln(SHRPRV)	3.22	1.38	0	4.60
AJDPRD	107	132	1	626
Ln(ADJPRD)	3.92	1.51	0	6.43
SUCESS	0.51	0.51	0	1
CMBSRD	483	349	40	1070
Ln(CMBSRD)	5.74	1.08	3.69	6.98
OWNSHR	31.6	30.3	1.16	100
Ln(OWNSHR)	2.98	1.16	0.15	4.61
INTRO	5.67	4.29	0	17
Ln(INTRO)	1.61	0.86	0	2.89

Table (4) Investment in Research and Development
Ordinary Least Square Estimation
Dependent Variable: Ln (Investment in Research and Development)
Number of Observations: 49

	(1)	(2)	(3)	(4)
C	4.11***	4.34***	4.12	3.61***
	(1.38)	(1.31)	(1.38)	(1.20)
Ln(Demand)	0.34	0.28	0.34	0.35*
	(0.27)	(0.27)	(0.27)	(0.26)
Ln(Hazard Rate)	0.90**	0.92**	0.90**	0.74**
	(0.43)	(0.42)	(0.43)	(0.43)
Contact+Proximity	-0.80**	-0.84**	-0.80**	-0.72**
	(0.37)	(0.36)	(0.37)	(0.36)
S&R.1 + S&R.2	0.86**	0.98**	0.86**	0.78**
	(0.43)	(0.43)	(0.43)	(0.44)
Architectural	-0.26	-0.38		
	(0.40)	(0.33)		
Incumbent			0.52	
			(0.36)	
Incumbent * Incremental	0.52*			
	(0.36)			
Incumbent * Architectural	0.15		-0.62**	
	(0.37)		(0.30)	
Entrant * Architectural			-0.26	
			(0.40)	
Ln(Previous Market Share)				0.14*
				(0.09)
Ln(Previous Market Share) * Incremental		0.14*		
		(0.08)		
Ln(Previous Market Share) * Architectural		-0.07		-0.15
		(0.11)		(0.16)
Ln(Previous Research Experience)				0.06
				(0.08)
Ln(Previous Research Experience) * Architectural				-0.02
				(0.13)
R2	0.59	0.60	0.59	0.60
F Statistic	8.49	8.92	8.48	7.4
R.S.S.	24.2.	23.5	24.2	23.9

Where *** Indicates significance at the 1% level, ** at the 5% level and * at the 10% level.

Table (5)

Project Success Rates by Innovation and Firm Type

Number of Projects
(As % of Total)

	Incumbents		
	Incremental	Architectural	Total
Successful Projects	13 (.72)	2 (.17)	15 (.50)
Failed Projects	5 (.28)	10 (.83)	15 (.50)
Total	18	12	30

	Entrants		
	Incremental	Architectural	Total
Successful Projects	4 (.44)	6 (.60)	10 (.51)
Failed Projects	5 (.56)	4 (.40)	9 (.47)
Total	18	12	30

Table (6) Technical Success.

Method of Estimation: Probit.

Dependent Variable: Technical Success of the Project.
Number of Observations: 49.

	(1)	(2)	(3)
C	0.03 (2.08)	0.03 (2.08)	-0.13 (2.04)
Ln(Hazard Rate)	0.84 (0.80)	0.84 (0.80)	0.81 (0.76)
Contact + Proximity	0.55 (0.77)	0.55 (0.77)	0.51 (0.72)
S&R.1 + S&R.2	-0.15 (0.78)	-0.15 (0.78)	-0.12 (0.76)
Ln(Research)	0.46* (0.34)	0.46* (0.34)	0.54* (0.30)
Ln(Research) * Architectural	0.25 (0.23)		0.13 (0.20)
Ln(Research) * Incumbent		0.15 (0.20)	
Ln(Research) * Incumbent * Incremental	0.15 (0.20)		
Ln(Research) * Prior Experience * Incremental			.02 (0.38)
Ln(Research) * Incumbent * Architectural	-0.46** (0.21)	-0.36** (0.14)	
Ln(Research) * Prior Experience * Architectural			-0.08** (0.04)
Ln(Reseach) * Entrant * Architectural		0.25 (0.23)	
Log Likelihood Function	-25.3	-25.3	-26.3

Where *** Indicates significance at the 1% level.
** Indicates significance at the 5% level.
* Indicates significance at the 10% level.

Standard errors are in parentheses.

Table (7) Commercial Success as a Function of Investment in Research

Method of Estimation: Tobit

Dependent Variable: Ln(Share of Market)
Number of Observations: 49

	(1)	(2)
C	5.49***	5.49***
	(1.12)	(1.12)
Ln(Competitive Investment)	-0.62***	-0.62***
	(0.19)	(0.19)
Ln(Time After First Introduction)	0.50	0.50
	(0.97)	(0.97)
Ln(Research)	0.03	0.02
	(0.27)	(0.27)
Ln(Research) * Architectural	0.44**	
	(0.20)	
Ln(Research) * Incumbent		0.14
		(0.18)
Ln(Research) * Incumbent * Incremental	0.14	
	(0.18)	
Ln(Research) * Incumbent * Architectural	-0.58***	-0.29***
	(0.18)	(0.13)
Ln(Reseach) * Entrant * Architectural		0.44**
		(0.20)
Log Likelihood Function	-76.5	-76.5

Where *** Indicates significance at the 1% level.
** Indicates significance at the 5% level.
* Indicates significance at the 10% level.

Standard errors are in parentheses.

Table (8) Commercial Success.as a Function of Technical Success

Method of Estimation: Tobit

Dependent Variable: Ln(Share of Market)
Number of Observations: 49

	(1)	(2)
C	4.11***	4.11***
	(1.04)	(1.04)
Technical Success	1.20***	1.20***
	(0.38)	(0.38)
Ln(Competitive Investment)	-0.39**	-0.39***
	(0.18)	(0.18)
Ln(Time After First Introduction)	0.59	0.59
	(0.49)	(0.49)
Architectural	0.56	
	(0.55)	
Incumbent		-0.17
		(0.50)
Incumbent * Incremental	-0.17	
	(0.50)	
Incumbent * Architectural	-1.32***	-0.59
	(0.54)	(0.49)
Entrant * Architectural		0.56
		(0.55)
Log Likelihood Function	-72.9	-72.9

Where *** Indicates significance at the 1% level.
** Indicates significance at the 5% level.
* Indicates significance at the 10% level.

Standard errors are in parentheses.

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